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**Final Report
NAG 8-494**

Analysis of Data from the HEAO-2/*Einstein* Observatory

MIT Center for Space Research

May 30, 1991

This is the final report for the MIT/HEAO-2 Data Analysis Grant. This research, which began with the launch of HEAO-2 (the *Einstein* Observatory) in 1978, continued under NASA Contract NAS8-30752 and NASA Grant NAG 8-494. It has led to many astrophysically significant discoveries which have been documented in the scientific literature (see publication lists in Appendix A). In addition to the direct scientific impact, the nation has benefited indirectly from the MIT efforts through the education of a large number of students (see Appendix B), and from the data that has been archived at the National Space Science Data Center and elsewhere. In this report we briefly summarize some of the more significant achievements of the MIT/HEAO-2 data analysis effort.

I. Analysis of Data from the Focal Plane Crystal Spectrometer (FPCS)

The Focal Plane Crystal Spectrometer (FPCS) was designed and built entirely at MIT. An X-ray spectrometer capable of resolving powers as high as $E/\Delta E \sim 1000$, the FPCS was used to resolve closely spaced X-ray emission lines and absorption edges, and to measure Doppler shifts resulting from bulk velocities $\sim 1000 \text{ km sec}^{-1}$. The FPCS performed flawlessly throughout the entire lifetime of HEAO-2.

Because of its high resolving power, the FPCS was able to isolate individual X-ray emission lines and absorption edges. The intensities of these features were then used as diagnostic tools in understanding the physics of the plasmas from which the X-ray emission arose. Examples include cooling flows in clusters of galaxies (in which the temperature distribution of the plasma and the rate of mass infall can be inferred, see, for example, references 2 and 27), the temperatures, elemental abundances, and ionization timescales of supernova remnants (refs. 6,9,10,11,33,64), the temperatures and loop structure of RS CVn stars (refs. 38,54), and detailed models of active galactic nuclei (ref. 77). In the case of the supernova remnant Cas A, Doppler shifts were measured which led to a detailed model of the kinematics of this object (ref. 33).

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II. Analysis of Data from the other HEAO-2 Instruments

MIT used the other instruments on HEAO-2 as well as the FPCS. A number of the publications in Appendix A resulted from studies made with the imaging instruments (the HRI and IPC) or the other spectrometers (the SSS and OGS) or the Monitor Proportional Counter, or some combination of the various instruments. Examples of the research performed with these instruments include studies of normal galaxies (ref. 45,57), cooling flows in clusters and in groups of galaxies (refs. 3,42,61, etc.), active galactic nuclei (refs. 4,7,25,29,37,46,50,58,60,63,etc.), supernova remnants (refs. 8,14,21,55,56), stars (refs. 5,13,15,18,34,40,62) and many others.

III. Other HEAO-2 Science

Many of the X-ray observations described above led to further work, either observations at other wavelengths, or more comprehensive developments of the underlying theory. Publications based on such followup and related studies form an important subset of the MIT HEAO-2 publication list. Some examples include observations at radio wavelengths of active galaxies previously studied in X-rays (references 16, 19, 39), development of cooling flow theory (refs. 27, 43, 49, 52, 70), theory of X-ray nebulae (refs. 32, 41, and 51), studies of pre-main sequence stars (refs. 31, 35), and others.

IV. Other Topics

A. Education

Nineteen MIT students have written Bachelor's or Master's theses based in whole or in part on HEAO-2 analysis. Six students received PhD degrees with theses largely dependent on HEAO-2 data. These students and their thesis titles appear in Appendix B.

B. Archival Material

An archival publication has been submitted to the *Astrophysical Journal (Supplements)* which summarizes all 400 observations made with the FPCS (reference 81). This will be of general use to scientists who need to know a flux (or upper limit) for a particular X-ray line from a particular object. For those who need more detailed information, we have submitted all of our raw data and a *User's Document* to the National Space Science Data Center (NSSDC). Furthermore, we are now completing a more user-friendly version of the data (in FITS format) which will be available on CD-ROM, or over the Internet from MIT, as well as at the NSSDC.

APPENDIX A

MIT Publications and Conference Contributions Based on HEAO-2 Data

May, 1991

A) MIT HEAO-2 Bibliography of Refereed Papers

1. "The *Einstein* (HEAO-2) X-Ray Observatory", R. Giacconi, G. Branduardi, U. Briel, A. Epstein, D. Fabricant, E. Feigelson, W. Forman, P. Gorenstein, J. Grindlay, H. Gursky, R. Harnden, J.P. Henry, C. Jones, E. Kellogg, D. Koch, S. Murray, E. Schreier, F. Seward, H. Tananbaum, T. Topka, L. Van Speybroeck, S.S. Holt, R.H. Becker, E.A. Boldt, P.J. Serlemitsos, G.C. Clark, C.R. Canizares, T.H. Markert, R. Novick, D. Helfand, and K. Long, *Ap. J.*, **230**, 540, 1979.
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8. "X-Ray Emission from Supernova Remnants near Gamma-ray Sources", R.C. Lamb and T.H. Markert, *Ap. J.*, **244**, 94, 1981.
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12. "Gravitational Focusing and the Association of Distant Quasars with Foreground Galaxies", C.R. Canizares, *Nature*, **291**, 620, 1981.
13. "*Einstein* X-Ray Identification of the Variable Radio Star LSI+61.303", G.F. Bignami, P.A. Caraveo, R.C. Lamb, T.H. Markert, and J.A. Paul, *Ap. J. (Letters)*, **247**, L85, 1981.
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B) Other Publications

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122. "Hot Gas and Heavy Halos in Elliptical Galaxies", C.R. Canizares, University of Michigan Astronomy Colloquium, March 1985 (invited).
123. Relativistic Jets in BL Lac Objects", C.M. Urry, Los Alamos National Laboratory Astrophysics Colloquium, March 1985 (invited).
124. "High Resolution X-Ray Spectroscopy of the Crab Nebula and the Oxygen Abundance of the Interstellar Medium", M.L. Schattenburg, Harvard-Smithsonian Center for Astrophysics Seminar, May 1985 (invited).
125. "High Resolution X-Ray Spectroscopy of the Crab Nebula and the Oxygen Abundance of the Interstellar Medium", M.L. Schattenburg, Massachusetts Institute of Technology Center for Space Research Seminar, May 1985 (invited).
126. "X-Rays from Galaxies and Clusters of Galaxies", C.R. Canizares, Dark Matter in the Universe (IAU Symposium No. 117), Princeton, June 1985 (invited).
127. "High Resolution X-Ray Spectroscopy of the Cygnus Loop", P.W. Vedder, C.R. Canizares, T.H. Markert, T. Pfafman, and A. Pradhan, *Bull. Am. Astron. Soc.*, **17**, 546, 1985.
128. "X-Ray and γ -Ray Observations of Astrophysical Jets", C.M. Urry, Workshop on Astrophysical Jets, Taos, New Mexico, July 1985 (invited).
129. "Hot Gas and Dark Matter in Galaxies and Clusters", C.R. Canizares, presented at SUNY Stony Brook Astronomy Colloquium, October 1985 (invited).
130. "The Violent Universe: High Energy Astrophysics", C.R. Canizares, presented at Congressional Staff Lecture Series on Science for the Non-Scientist, Washington, D.C., November 1985 (invited).
131. "X-Ray Studies of Seyfert Galaxies and Quasars", C.R. Canizares, presented at I.A.U. Symposium #119, Quasars, Bangalore, India, December 2-6, 1985 (invited).
132. "X-Ray Absorption in BL Lac Objects", C.M. Urry, Boston University Astronomy Colloquium, December 1985 (invited).
133. "X-Ray Spectra of BL Lac Objects: Evidence for Absorption by Hot Gas", C.M. Urry, Massachusetts Institute of Technology Astrophysics Colloquium, December 1985 (invited).
134. "X-Ray Continuum Emission from BL Lacertae Objects", C.M. Urry, Workshop on Continuum Emission from Active Galactic Nuclei, Tucson, Arizona, January 1986 (invited).

135. "The X-Ray Structure and Spectrum of IC443", R. Petre, A. Symkowiak, F. Seward, C.R. Canizares, R. Willingale, D. Rolf, N. Woods, 167th Meeting of the Amer. Astron. Soc., Houston, *Bull. Amer. Astron. Soc.* **17**, 883, January 1986.
136. "X-Ray Spectra of BL Lac Objects: Evidence for Absorption by Hot Gas", C.M. Urry, Columbia University Astrophysics Colloquium, February 1986.
137. "BL Lac Objects", C.M. Urry, ESA Conference on Accretion onto Compact Objects, Tenerife April 1986 (invited).
138. "X-Ray Structure and Spectroscopy of Supernova Remnants", C.R. Canizares presented at the Meeting of the American Physical Society, Washington, April 1986, *Bull. Amer. Phys. Soc.*, **31**, 829, 1986 (invited).
139. "Properties of the X-Ray Emitting Gas in Early Type Galaxies", C.R. Canizares, G. Fabbiano and G. Trinchieri, presented at I.A.U. Symposium #127, Structure and Dynamics of Elliptical Galaxies, Princeton, May 1986.
140. "Steady State Infall Models of Gas in Elliptical Galaxies", P.W. Vedder, C.R. Canizares, and J. J. Trester, 168th Meeting of the Amer. Astron. Soc., Ames, Iowa, *Bull. Amer. Astron. Soc.*, **18**, 691, June 1986.
141. "High Resolution X-Ray Spectroscopy of Cas A: A Non-Equilibrium Interpretation", T.H. Markert, C.R. Canizares, P.L. Blizzard, and J.P. Hughes, 168th Meeting of the Amer. Astron. Soc., Ames, Iowa, *Bull. Amer. Astron. Soc.* **18**, 704, June 1986.
142. "Seven Years of IUE Observations of the BL Lacertae Object PKS2155-304", C.M. Urry, International IUE Conference, in London, July 1986.
143. "Accretion Flows in Elliptical Galaxies", P.W. Vedder, in *Continuum Radio Processes in Clusters of Galaxies*, NRAO - Green Bank #16, edited by C.P. O'Dea and J.M. Uso, p. 127, August 1986.
144. "Variability of Active Galaxies Observed with the *Einstein* Observatory", C.M. Urry, Conference on X-Ray Variability, in Como Italy, October 1986.
145. "BL Lacertae Objects: What Kind of Active Galaxy are They?", C.M. Urry, Colloquium of the Osservatorio Arcetri in Florence, Italy, October 1986.
146. "Hot Gas in Galaxies and Clusters of Galaxies", C.R. Canizares, University of California at Berkeley Physics Colloquium, November 1986 (invited).
147. "Current Ideas About BL Lacertae Objects", C. M. Urry, Marshall Space Flight Center Astrophysics Colloquium, December 1986.
148. "X-Ray Variability of Seyfert Galaxies Observed with the *Einstein* Observatory", C.M. Urry, C.R. Canizares, J.S. Kruper, M.L. Rohan, M.R. Oberhardt, *Bull. Amer. Astron. Soc.*, **18**, 1000, 1987.
149. "Soft X-Ray Spectra of Seyfert Galaxies", J.S. Kruper, C.M. Urry, C.R. Canizares, *Bull Amer. Astron. Soc.*, **18**, 1001, 1987.

150. "Hot Gas in Galaxies and Clusters of Galaxies", C.R. Canizares, Columbia University Astrophysics Colloquium, January 1987 (invited).
151. "Cooling Flows in Galaxies and Clusters", C.R. Canizares, University of Colorado at Boulder Astrophysics Colloquium, March 1987 (invited).
152. "Hot Gas in Galaxies and Clusters of Galaxies", C.R. Canizares, Northeastern University Physics Colloquium, March 1987 (invited).
153. "Soft X-Ray Spectra and Variability of Seyfert Galaxies", C.M. Urry, The Johns Hopkins University Astrophysics Seminar, March 1987.
154. "Soft X-Ray Spectra and Variability of Seyfert Galaxies", C.M. Urry, The University of Maryland Astronomy Colloquium, March 1987.
155. "On Cooling Flows and Hot gas in Galaxies and Clusters", C.R. Canizares, University of Virginia Astrophysics Colloquium, April 1987 (invited).
156. "X-Ray Emission Lines from Cooling Flows", C.R. Canizares, NATO Advanced Study Workshop, Institute of Astronomy, Cambridge, U.K., June, 1987 (invited).
157. "Narrow-Band H α Imaging of Early-Type Galaxies", P.W. Vedder, C.R. Canizares, and Paula L. Blizzard, presented at the 170th Meeting of the American Astronomical Society, Vancouver, British Columbia, Canada, 1987.
158. "Are Elliptical Galaxies Really Round?" J.L. White and C.R. Canizares, presented at the 170th Meeting of the American Astronomical Society, Vancouver, British Columbia, Canada, 1987.
159. "Ultraviolet Spectra of the Variable BL Lacertae Object PKS 2155-304", C.M. Urry, to be presented at the 170th Meeting of the American Astronomical Society, Vancouver, British Columbia, Canada, 1987.
160. "Ionization Structure of the X-Ray Emitting Plasma in Puppis A", K.F. Fischbach, C.R. Canizares, T.H. Markert, and J.M. Coyne, presented at the 170th Meeting of the American Astronomical Society, Vancouver, British Columbia, Canada, 1987.
161. "Einstein Bragg Crystal Spectrometer Observations of Cas A - A Two Region, Non-Equilibrium Ionization Interpretation", T.H. Markert, P.L. Blizzard, C.R. Canizares, and J.P. Hughes, presented at IAU Colloquium 101, *The Interaction of Supernovae and the Interstellar Medium*, Penticton, British Columbia, Canada, June 1987.
162. "Plasma Diagnostics with X-ray Lines of Oxygen in Puppis A", K.F. Fischbach, C.R. Canizares, T.H. Markert, and J.M. Coyne, presented at IAU Colloquium 101, *The Interaction of Supernovae and the Interstellar Medium*, Penticton, British Columbia, Canada, June 1987.
163. "X-ray Emission Lines from SNRs and Clusters of Galaxies", C.R. Canizares, Lawrence Livermore National Laboratory, Livermore, CA, October, 1987 (invited).
164. "Hot Gas in Galaxies and Clusters", C.R. Canizares, Cornell Astronomy Colloquium, Ithaca, NY, March 1988 (invited).

165. "A Comparison of Three Regions of Puppis A", K.F. Fischbach, L.M. Bateman, C.R. Canizares, T.H. Markert, and P.J. Saez, presented at IAU Colloquium No. 115 *High Resolution X-Ray Spectroscopy of Cosmic Plasmas*, Cambridge, Massachusetts, 1988.
166. "High Resolution Spectroscopy and Plasma Diagnostics of Supernova Remnants", C.R. Canizares, presented at IAU Colloquium No. 115 *High Resolution X-Ray Spectroscopy of Cosmic Plasmas*, Cambridge, Massachusetts, 1988.
167. "High Resolution X-Ray Spectroscopy of Thermal Plasmas", C.R. Canizares, *Einstein* to AXAF Symposium, Cambridge, MA, November, 1988 (invited).
168. "X-Ray Observations of Supernova Remnants", C.R. Canizares, NATO Workshop on Physical Processes in Hot Cosmic Plasmas, Vulcano, Italy, June, 1989 (invited).
169. "Cooling Flows in Clusters of Galaxies", C.R. Canizares, UCSD Astrophysics Colloquium, San Diego, CA, March, 1991 (invited).
170. "Cooling Flows in Clusters of Galaxies", C.R. Canizares, Caltech Astrophysics Colloquium, Pasadena, CA, March, 1991 (invited).
171. "Cooling Flows in Clusters of Galaxies", C.R. Canizares, University of Toronto Astrophysics Colloquium, Toronto, Canada, March, 1991 (invited).
172. "X-ray Spectroscopy of the Supernova Remnant N132D", U. Hwang, C.R. Canizares, T.H. Markert, and J.P. Hughes, 1991, *Frontiers of X-ray Astronomy*, Yamada, Japan, April 1991.

APPENDIX B
MIT THESES BASED on HEAO-2 DATA

Doctor of Philosophy

- Petre, R., 1982, *Wide-Field Imaging in Soft X-ray Astronomy*
- Kriss, G.A., 1982, *X-ray and Optical Studies of Active Galactic Nuclei and Quasi-Stellar Objects*
- Schattenburg, M.L., 1984, *Astronomical X-ray Spectroscopy: Studies of the Crab Nebula and Development of Ultra-Fine Transmission Gratings*
- Kruper, J., 1988, *Optical and X-ray Studies of Active Galactic Nuclei*
- Vedder, P.W., 1988, *Optical Observations and Numerical Models of Gas Cooling Flows in Elliptical Galaxies*
- Flanagan, K.A., 1990, *Plasma Diagnostics with X-ray Emission Lines of Puppis A*

Master of Science

- Culver, J.A., 1983, *Optical and X-ray Studies of Cooling Flows in Clusters of Galaxies*
- Rohan, M.L., 1985, *An X-ray Scattered Halo in M82?*

Bachelor of Science

- Dietz, E.R., 1973, *A comparative Study of the Flat and Spherically Curved Forms of Three Soft X-ray Bragg Diffractors*
- Davies, N.J., 1974, *An Evaluative Study of Three Crystals Utilizing the Double Crystal Spectrometer*
- Smith, D., 1975, *Characterization of Crystals for X-ray Diffraction*
- Flanagan, K.A., 1976, *Investigations of a Seven Wire Imaging Proportional Counter*

- Berg, C.J., 1977, *Geometry of a Crystal Spectrometer for X-ray Astronomy*
- Waite, C.M., 1981, (B.A., Middlebury College), *Paradoxical Emission from Two X-ray Supernova Remnants*
- Bromley, B.C., 1982 (B.A., Middlebury College), *X-ray Spectroscopy of Supernova Remnants: the Bright Knot of Puppis A*
- Campbell, G., 1982, *An X-ray Point Source in the Supernova Remnant G27-4+0.0*
- Perkins, F.K., 1982, *Analysis of the X-ray Spectra of N132D*
- Rallis, A.D., 1982, *High Resolution X-ray Observations of M33*
- Vedder, P.W., 1982, *X-ray Imaging Observations of the Central Stars of Planetary Nebulae*
- Donahue, M.E., 1985, *X-ray Observations of the Pegasus Cluster*
- Wargelin, B.J., 1985, *Low Energy X-ray Spectra of 16 X-ray Binaries*
- White, J., 1987, *Are Elliptical Galaxies Really Round?*
- Sokoloski, J., 1989, *Fourier Analysis of Seyfert Galaxy X-ray Variability*
- Kim, L.D., 1989, *Optical Studies of Cooling Flows in Elliptical Galaxies*
- Moore, C., 1990, *High Resolution X-ray Spectroscopic Measurements of the Tycho Supernova Remnant*